

Design and Analysis of a Novel MEMS Piezoresistive Pressure Sensor with Annular Groove Membrane and Centre Mass for Low Pressure Measurements

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Research Article

Keywords: Silicon Diaphragm, Annular groove, Centre mass, Square membrane, MEMS piezoresistive sensor

Posted Date: May 7th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-430347/v1>

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TITLE PAGE

CONCISE AND INFORMATIVE TITLE

Design and analysis of a novel MEMS piezoresistive pressure sensor with annular groove membrane and centre mass for low pressure measurements

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Structured Abstract

Purpose: Micro Electronic Mechanical System (MEMS) based pressure sensors have found their use in multiple applications lately in the field of healthcare, automotive etc. These sensors however face a trade-off between sensitivity and linearity which limits sensor performance. The proposed design aims to achieve an enhanced sensor performance by alleviating the sensitivity and linearity trade-off.

Methods: Novel structures such as annular grooves and center mass have been introduced for providing better sensor performance along with membrane dimension optimization. Annular grooves generate Stress Concentrated Regions (SCRs) on membrane surface on application of external pressure which enhances sensor sensitivity while center mass provides partial stiffening of the membrane and hence reduces non-linearity.

Results: The proposed sensor achieves a low non-linearity error of 0.15% FSS with a well-balanced sensitivity of 28.0 mV/V/psi.

Conclusion: The proposed novel sensor structure achieves a relatively better performance in comparison to conventional membrane variants. With a high sensitivity and appreciable linearity, the novel structure proves to be ideal for low pressure measurements in the range (0-5)KPa.

Keywords: Silicon Diaphragm, Annular groove, Centre mass, Square membrane, MEMS piezoresistive sensor

Declarations:

Funding- Not Applicable.

Conflicts of interest/Competing interests –Not Applicable.

Availability of data and material- Not Applicable.

Code availability- Licensed Version of MATLAB & COMSOL has been used to generate plots.

Authors' contributions- Optional (Not Applicable).

I. INTRODUCTION

Micro electromechanical system (MEMS) based piezoresistive pressure sensors find wide scale use because of their small size, relatively low cost, simple fabrication and Direct Current (DC) output. Micro electromechanical piezoresistive pressure sensors have found their use in automobile, aerospace and petrochemical industry etc for pressure measurements. The basic principle behind this sensor is based on a slender membrane which shows deflection when a pressure is exerted externally on the surface of the membrane. This deflection is measured using a Wheatstone bridge which gives a proportionate voltage output[1].

There is a trade-off between linearity and sensitivity, especially for low pressure measurements in piezoresistive pressure sensor [2][3] and hence the design and fabrication of these piezoresistive pressure sensors require acute balancing between the two. The membrane sensitivity varies in proportion to the ratio of membrane length a and membrane thickness h , which can be improved by adjusting the membrane dimensions [3]. However, the nonlinearity error of the membrane increases with this ratio at a much faster

rate, because of the fact that error in nonlinearity of the pressure-to-stress conversion is proportional to $\left(\frac{a}{h}\right)^4$ [4]. This effect has been described as the “balloon effect” [5]. Many previous works have been performed aiming to assuage the contradiction between sensitivity and non-linearity. Most of these works are centered around the use of stress concentration regions (SCRs) for sensitivity enhancement while some concentrate on the use of membrane stiffening/modification techniques in order to reduce deflection and hence non-linearity. The SCRs allow utilization of higher strain energies by the piezoresistors, when these resistors are placed on the SCRs thereby improving the sensitivity. A cross beam structure on a membrane in order to produce SCRs was proposed for low pressure measurements [6]. Similarly an accelerometer with a beam-mass membrane which obtained a considerable sensitivity was simulated [7]. A beam-membrane-dual-island structure was proposed based on the concept of SCR which proved defective in producing high sensitivity level ($17.339 \mu\text{V/V/Pa}$)[8].

The membrane deflection increases the slope of the output curve, adding to the variation between the actual output and the ideal linear output [9]. This leads to a large ascend in the pressure nonlinearity error (PNL). In order to minimize this deflection, stiffening of the membrane is done using various methods. A sensor with a thin-walled hollow stiffening structure was developed on a thin silicon diaphragm, obtained a non-linearity of less than 0.40% FS (Full Scale) [10]. A bossed membrane piezoresistive pressure sensor was designed with its nonlinearity error reaching as low as 0.14% FSS for applications involving low pressure [11]. Similarly a novel diaphragm installed with a boss and peninsula-island structure used for membrane stiffening was proposed [12] and it obtained a low nonlinearity error for its operating range. It is fair enough to deduce that producing SCRs and reducing deflection are the two main aspects of obtaining good sensor characteristics i.e. high sensitivity along with low nonlinearity error.

This work proposes a novel structure with annular grooves on a membrane. The membrane is stiffened using a square-shaped center mass in order to envisage the electromechanical response of a piezoresistive pressure sensor for pressure range of (0-5)KPa. The proposed structure is modeled and analyzed using finite element method(FEM) analysis with the help of COMSOL Multiphysics software. An estimation of the stress distribution and analysis of the deflection of proposed structure is made. In comparison to the existing literature an attempt has been made to alleviate the trade-off between sensitivity and linearity and realize a micro size sensor for low pressure measurement with considerably high accuracy.

II. DESIGN AND PRINCIPLES

High stress and linear output are the two factors which characterize sensor performance. While large membranes provide high sensitivity, they lack adequate linearity. The vice versa is true for membranes smaller in size. The proposed sensor design uses a square membrane rather than a rectangular or circular because of its higher stress generation [13]. The elasticity theory illustrates the maximum stress for the square membrane[17] as

$$\sigma_{SM} = 0.308 \left(\frac{L}{H} \right)^2 (1 - \mu^2) \quad (1)$$

Here, H is the membrane thickness; μ refers to the Poisson ratio, L is the length of sides of the square membrane. The maximum stress developed in a square membrane is 15% more than that of a rectangular membrane and 60% more than the circular one [16].

Oversized membrane deflection is one of the critical causes of non-linearity between pressure and deformation of the membrane. The dependence of deflection on the pressure applied remains linear as long as the small deflection theory is satisfied. When the deflection exceeds a definite fraction of the membrane thickness, the large deflection theories work, leading to the nonlinearity between pressure and deflection as discussed. In order to maintain linearity, the deflection (w_{\max}) should be lesser than 1/5 of the membrane thickness[15] where:

$$w_{\max} = \frac{0.0152PL^4(1-\nu^2)}{EH^3} \quad (2)$$

Here P is the pressure applied, E is the Young's modulus and H refers to thickness of the membrane. Reduced membrane deflection helps to establish low nonlinearity along with high stability. The proposed structure hence aims to minimize deflection through a novel structure that has been discussed in the subsequent section.

III. STRUCTURE DESIGN

The design is characterised by an annularly grooved membrane supported via a square central mass as shown in Fig1a and Fig 1b. Square diaphragm are easy and cost effective to fabricate for pressure sensors using anisotropic wet etchants as they have better sensitivity and produce relatively higher stress[20]. The substrate used for the sensor chip is N-type silicon wafer due to its unique mechanical properties [15]. Four grooves are present with ribs between each of them on the membrane's front side. Annular grooves promote the formation of High Concentrated Stress Profile (HCSP) which increases the membrane sensitivity. The dimensions of the groove are 60 μm in width and 10 μm in depth while the membrane dimensions are 3600 μm in length and 30 μm in thickness.

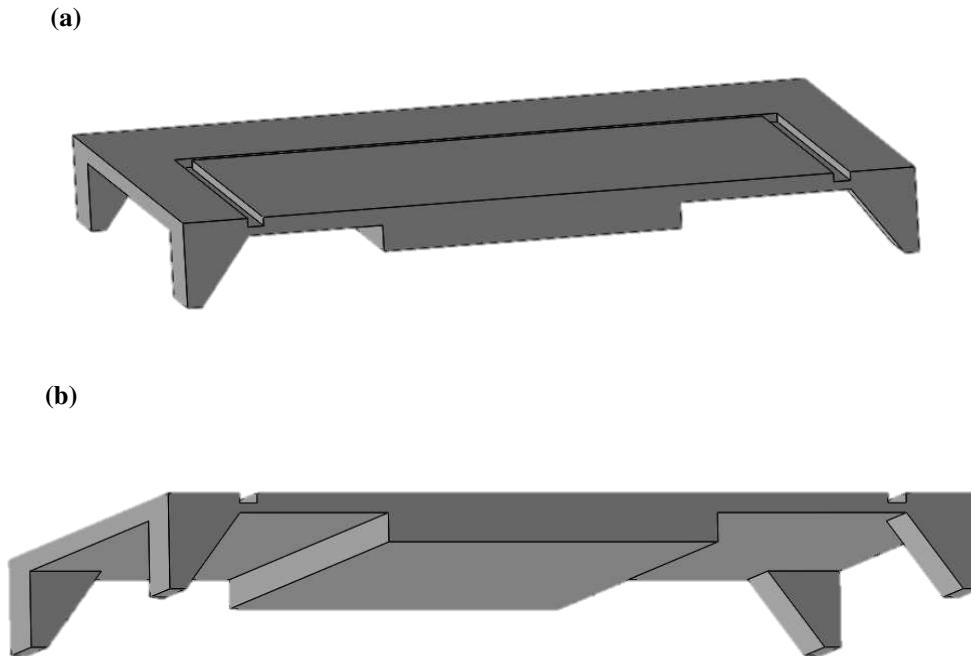
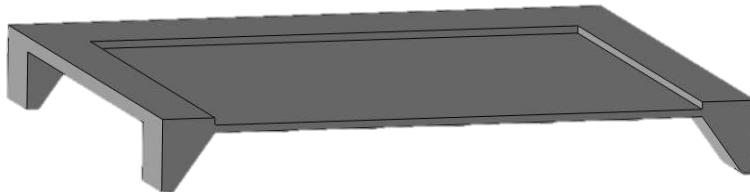


Fig.1 Structure of proposed membrane: (a) Front view (b) Rare view

The centre mass in the proposed design accounts for the stability of the membrane and reduces the non-linearity error between pressure and membrane deflection. Based on the small deformation theory, the central mass pattern contributes to the stiffness change and decreases the pressure nonlinearity to smaller than 1.0% FSS[19].The performance of the sensor is affected by the thickness of the central mass. According to the simulation results, membrane sensitivity does not vary much on increasing the thickness of centre mass beyond 50 μm [14].Hence the thickness of the square centre mass has been chosen as 50 μm . and the side length as 1200 μm .

(a)



(b)

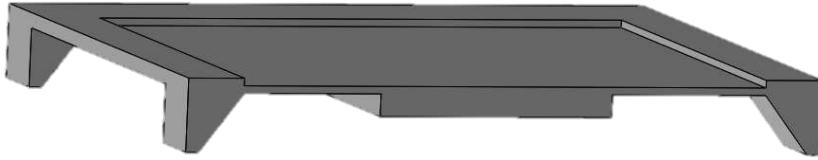


Fig.2 Conventional membranes: (a) C-type membrane (b) E-type membrane

IV. GEOMETRY ANALYSIS

The deflection and sensitivity of the membrane is determined by its geometry. The proposed geometry has been analysed with respect to the conventional C and E type membranes in terms of both deflection and sensitivity as parameters. A conventional flat square membrane is referred to as a C-type membrane as shown in Fig.2a. On the other hand an E-type membrane consists of a membrane with a centre mass as shown in Fig.2b. Finite element method (FEM) analysis was performed for the conventional C and E type membranes as well as for the proposed membrane. The membrane dimensions for the conventional membranes considered for comparison with proposed structure has been chosen as 3600 μm , same as that of the latter. N-type silicon has been used as material for the conventional membranes as well as the proposed membrane. The applied pressure was gradually increased from 0KPa to 5KPa. The deflection and stress plots are obtained through FEM analysis using COMSOL Multiphysics software. It has been used for comparing linearity and sensitivity of the proposed membrane with that of the conventional membranes. The output sensitivity depends directly on the stress generated on the membrane surface. For a conventional C-type square membrane, the stress distribution at the SCRs and the central deflection are given as Eq.(1) and Eq.(2) respectively.

The stress distribution for a C-type membrane has been shown in Fig.3a. As it is evident, maximum stress is observed at the middle of the pedestal sides. While the C type produces considerable stress, its membrane stability remains a critical issue leading to large deflection.

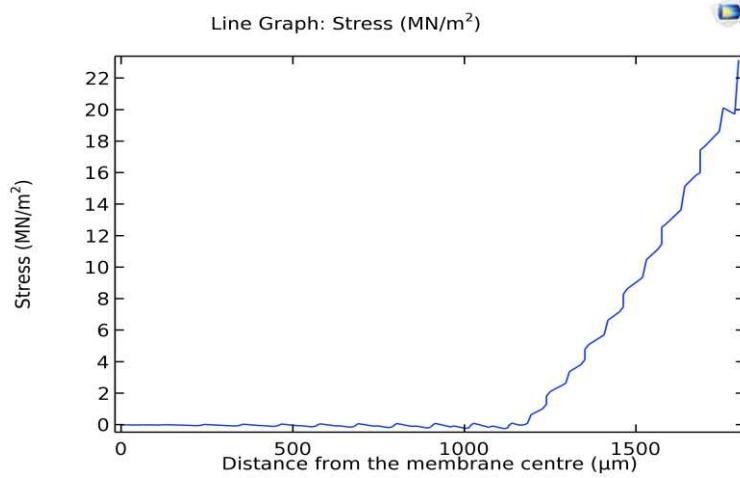
The issue of deflection in the case of C type as seen in Fig.3b is addressed using an E-type membrane which introduces a centre mass. The centre mass locally stiffens the membrane and reduces deflection considerably. The central deflection ω_E and the stress σ_E at the SCRs for the E-type membrane are given as Eq.(3) and Eq.(4) respectively[14]

$$\omega_E = 0.0152 \left(\frac{PL^4}{EH^3} \right) (1 - \nu^2) \left[1 - \left(\frac{l}{L} \right)^4 + 4 \left(\frac{l}{L} \right)^2 \ln \frac{l}{L} \right] \quad (3)$$

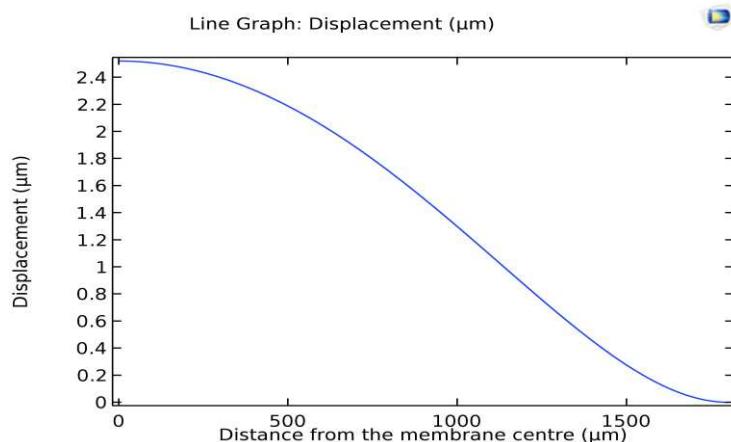
$$\sigma_E = 0.308P \left(\frac{L}{H} \right)^2 (1 - \nu^2) \left[1 - \left(\frac{l}{L} \right)^2 \right] \quad (4)$$

Here l is the length of central mass, P is the applied pressure, L refers to the side length of the square membrane while H denotes the membrane thickness. E and ν refers to Young's modulus and Poisson's ratio respectively. The stress and the deflection for the E-type membrane varies with distance from the membrane centre and is shown in Fig.3c and Fig.3d respectively.

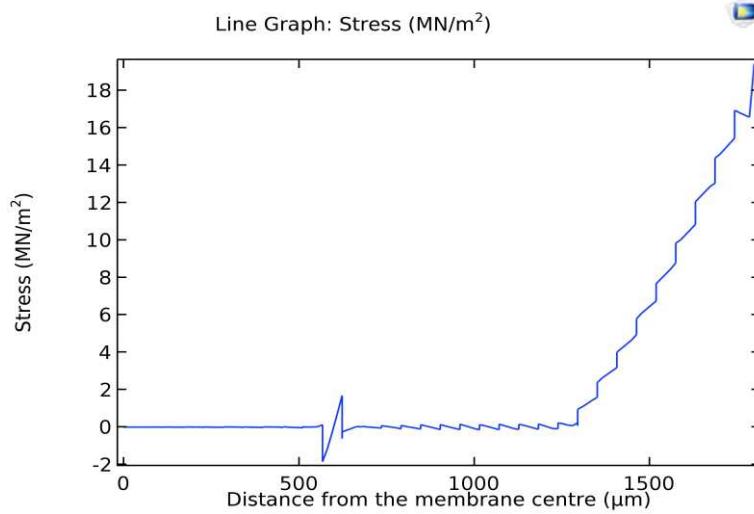
(a)



(b)



(c)



(d)

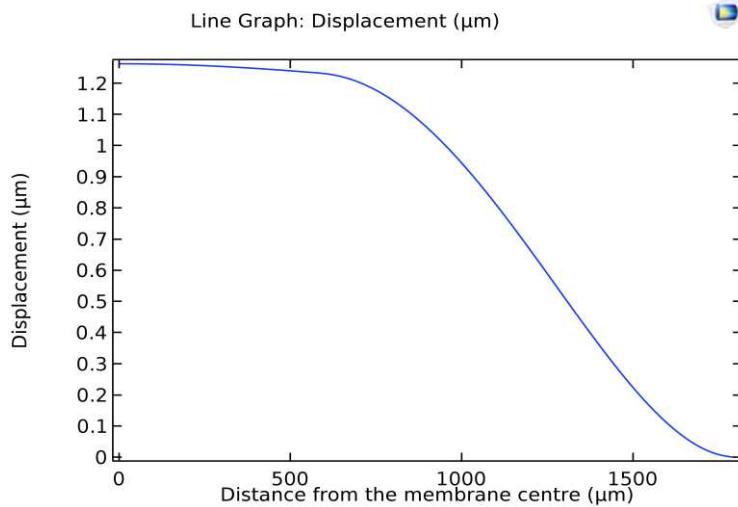


Fig.3 (a) Stress for C-type membrane (b) Displacement for C-type membrane (c) Stress for E- type membrane (d) Displacement of E-type membrane

For balancing the trade off between sensitivity and non linearity a grooved membrane with a central mass is used here. The annular grooved structure determines the sensitivity of the membrane. Compared to the conventional membrane structures shown above, proposed membrane attains a better sensitivity due to the grooved structure and lower non-linearity as a result of the incorporation of central mass similar to E-type membrane. The nonlinearity is less due to lesser deflection and stabilization provided by the centre mass. The membrane has some conformity with the E-I type membrane and its central deflection ω is given as [17]

$$\omega = \frac{\pi L^2 b^3}{8bg^3 E(1+\beta)} P - \frac{3[1+\beta(g/H)^2]}{4(1+\beta)^2 g^2} \omega^3 \quad (5)$$

Where

$$\beta = \frac{2gbE + g(\pi LE - 2bE)}{\pi LbD} \quad (6)$$

and

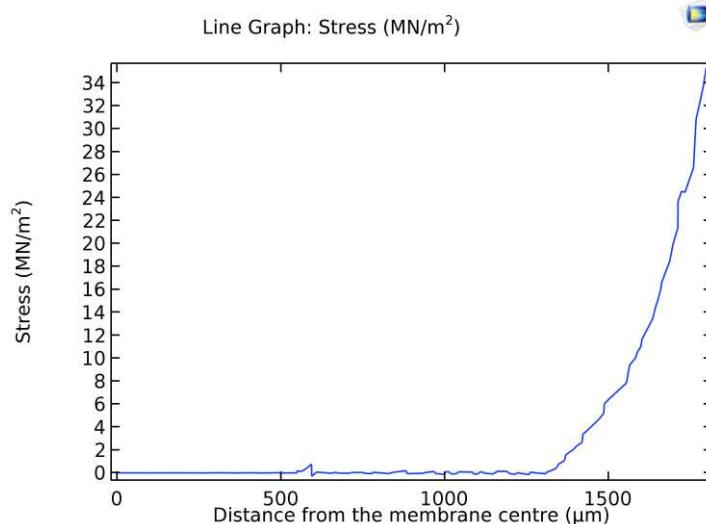
$$D = \frac{EH^3}{12(1-\mu^2)} \quad (7)$$

where ω refers to the deflection of the membrane, β refers to a coefficient as mathematically defined above in Eq.(6), D denotes the flexural rigidity, b and g are groove width and depth respectively; L and H are length and thickness of the membrane respectively. Here E is the Young's elastic modulus and P is the applied pressure. Here in the equation for central deflection, the first part of the Eq.(5) refers to the rib bending strain while the second portion of Eq.(5) denotes the membrane deforming strain. Central deflection ω can be reduced by decreasing the groove depth g and groove width b . The deflection can be further decreased by the addition of a central mass. The centre mass will reduce the bending and membrane deforming strain and provide stability to the membrane. The central mass causes a reduction in deflection by a factor x given in Eq.(8) i.e.

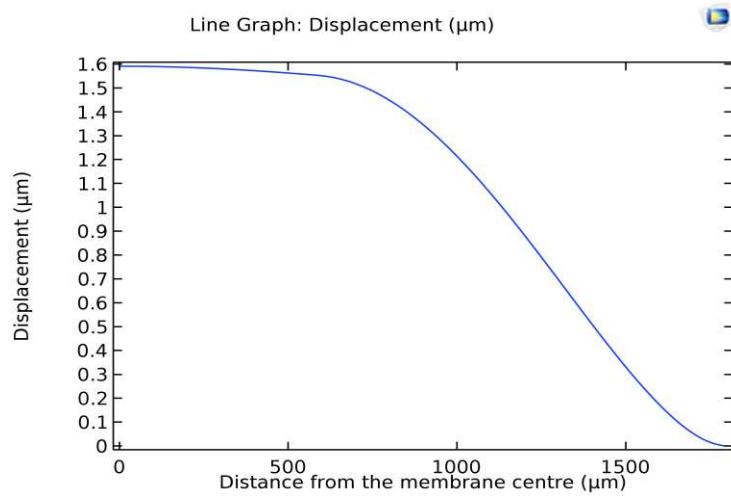
$$x = \left[1 - \left(\frac{l}{L} \right)^4 + 4 \left(\frac{l}{L} \right)^2 \ln \frac{l}{L} \right] \quad (8)$$

Where l is the length of central mass and L is the membrane side length. So the membrane deflection as given in Eq.(7) is reduced by this factor thus leading to reduced deflection and hence better linearity.

(a)



(b)



(d)

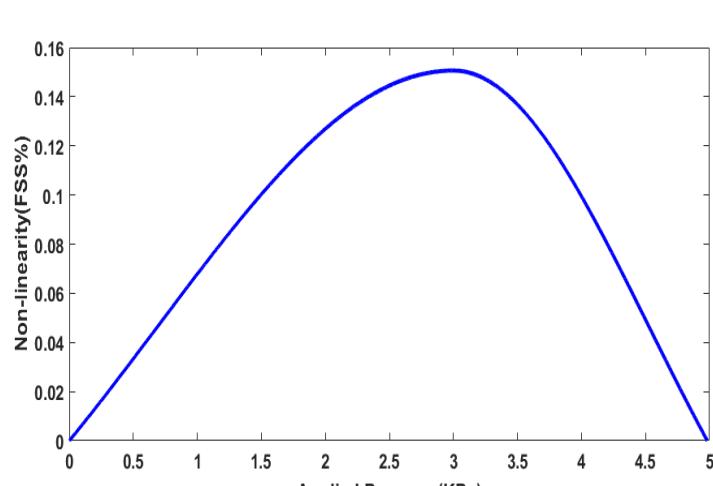


Fig.4 (a) Stress for proposed membrane (b) Displacement for proposed membrane (c) Output vs. applied pressure of proposed membrane (d) Non linearity vs. applied pressure for proposed membrane

The stress distribution for the proposed membrane is shown in Fig.4a. The membrane proposed in this work achieves 76.01% higher stress generation than E-type and 47.73% than C-type membrane. Moreover, the novel structure attains deflection as shown in Fig.4b which is 38.4% smaller than the conventional C-type membrane and approximately 11.11% smaller deflection than a conventional E-type membrane. The stress values obtained from COMSOL at different applied pressure were used to calculate the proposed sensor output and non-linearity. The output and non-linearity values with respect to varying applied pressure were used to obtain Fig.4c and Fig.4d respectively using MATLAB. The sensitivity of the membrane can be interpreted from the slope of the output vs. pressure plot as shown in Fig.4c. The proposed membrane achieves appreciable sensitivity with minimal non-linearity as depicted in Fig.4d.

In this work, COMSOL Multiphysics software has been used to analyse the performance of the membrane through FEM analysis. The membrane dimensions for the study have been defined as (3600 x 3600) μm and a thickness of 30 μm is taken. Piezoresistive property is found in several materials like Silicon, Polysilicon and SiC. Silicon is well suited here because of its small size, less weight and small power constraints. It also has a wide variety of CMOS compatible process options. The material used for the proposed structure is N-type Silicon[18] having properties as shown in Table1.

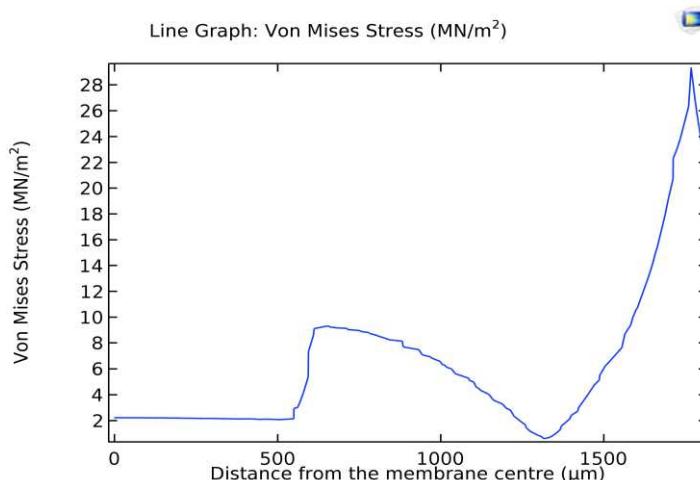
Table1. Properties for N-type silicon

Properties	Values	Properties	Values
Density (kg/m ³)	2330	Yield strength (GPa)	7
Band gap(eV)	1.1	Hardness (kg/mm ²)	1000
Poisson ratio	0.28	Young elastic modulus (GPa)	169

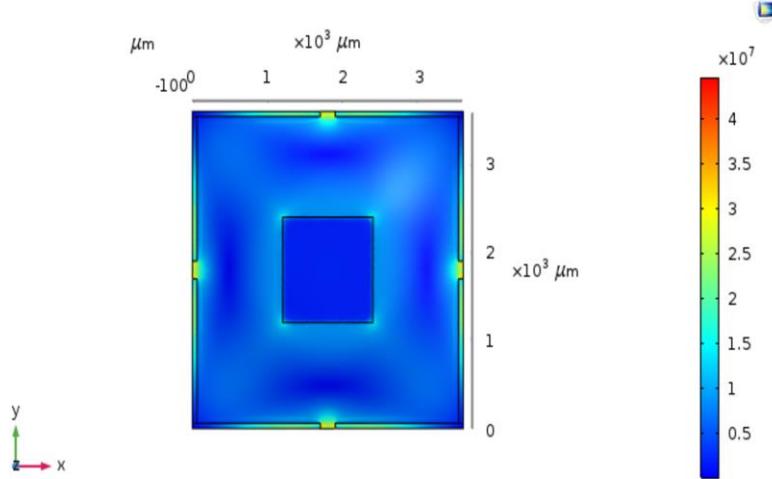
V. FEM ANALYSIS

The boundary conditions are applied on the interface between chip and the glass. The number of elements in the finite element model (FEM) is 26738. The pressure applied is set at 5KPa. The Von-Mises stress distribution for the analysed structure has been depicted in Fig.5a.

(a)



(b)

**Fig.5 (a) Von-Misses stress (b) Surface Stress distribution for proposed membrane**

The Fig.5b illustrates concentration of stress around the rib. The stress concentrated regions occur at the rib surface indicated by the reddish yellow around the hinge and are called HCSP. The output of the sensor varies in proportion with the differential stress at the piezoresistor area and is given in Eq.(9)[17]

$$U_{out} = \frac{1}{2} \pi_{44} (\sigma_l - \sigma_t) U_{in} = \frac{1}{2} \pi_{44} \sigma_R U_{in} \quad (9)$$

Here π_{44} denotes the shear piezoresistive coefficient, σ_t refers to the transversal stress and σ_l is the longitudinal stress, U_{out} refers to the output voltage while U_{in} denotes the input voltage. It is evident that the output voltage depends on σ_R i.e. differential stress. For attaining maximum sensitivity, piezoresistors must be placed at the HCSP regions. The stress are mainly concentrated within a small range ($\pm 100 \mu\text{m}$), which means the strain energy is strictly restricted in a narrow area on the surface of the rib region and the energy does not spread outside the HCSP [17]. The maximum strain energy is used by the four piezoresistors when the longitudinal piezoresistors are placed along x direction lengthwise while the transversal ones are located in the y-direction breadthwise. The deflection of the membrane varies with the distance from the membrane centre. It is observed that maximum deflection occurs at the membrane centre while it is negligible at the fixed membrane boundaries/edges.

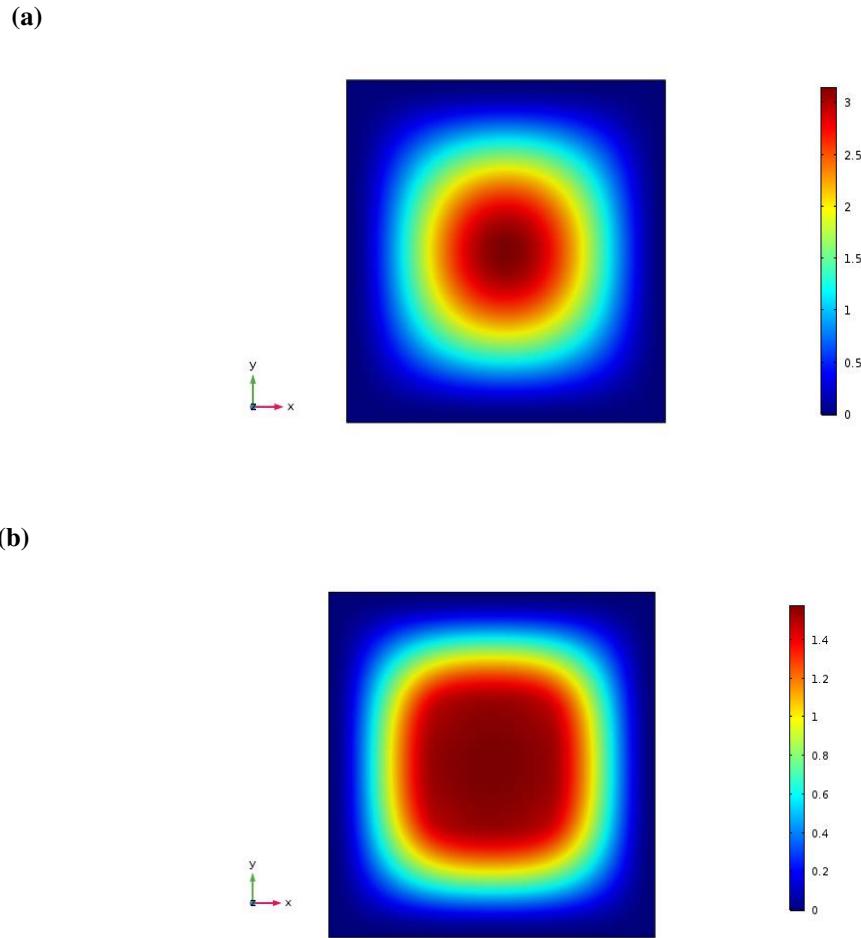


Fig.6 (a) Membrane deflection without central mass (C-type) (b) Membrane deflection with central mass (E-Type)

The higher membrane deflection as observed in Fig.6a is minimized to a deflection of $1.6\mu\text{m}$ with the introduction of centre mass as evident in Fig.6b. The red colour signifies maximum deflection at the centre. The deflection is lessened due to central mass under the membrane. In the conventional E-type membrane sensitivity is also reduced to obtain low deflection. However in the proposed structure the sensitivity is much better as compared to the E-type.

VI. RESULTS AND DISCUSSION

6.1 Membrane Dimension Analysis

The sensitivity and deflection of the membrane is highly critical of the membrane size. Larger dimensions of membrane provide good sensitivity but have significant deflection whereas it is vice versa for smaller membranes. Hence it becomes important to choose appropriate dimensions for better performance of the membrane. The optimized membrane size was obtained by varying the dimensions of the proposed square membrane. The membrane side length was varied over a range of $(2400-4800)\mu\text{m}$ along with changing the centre mass dimensions in proportion to the varying membrane dimensions. The following were observed as stated in Table 2.

Table 2. Comparison between various membrane sizes

Membrane side length (μm)	Stress (KPa)	Deflection(μm)
2400	16	0.32
3600	34	1.6
4800	65	5

Through the results it was perceived that the membrane was able to attain an appropriate balance between sensitivity and deflection for the membrane dimension of $(3600 \times 3600)\mu\text{m}$. The deflection was observed to be $1.6\mu\text{m}$ while the maximum stress incurred was $34\mu\text{m}$ over a pressure range of $(0-5)\text{KPa}$. Consequently, an appreciable sensitivity of 28mv/KPa was observed for the proposed membrane dimension.

The thickness of the membrane impacts its sensitivity. As the membrane thickness increases, the Von Mises stress produced decreases so it is better to keep a lesser membrane thickness. However a very thin membrane will destabilize it and lead to a high non linearity error. So the optimum value chosen for the membrane thickness is $30\mu\text{m}$.

After analysing different dimensions for the membrane, it was inferred from the simulation results that at the proposed dimensions, the membrane tends to attain a satisfactory equilibrium between sensitivity and deflection.

6.2 Centre Mass Dimensions

The centre mass thickness is chosen to be $50\mu\text{m}$ because there is only $(0.4- 0.5)\%$ decrease in non-linearity error when the thickness is increased from $50\mu\text{m}$ to $70\mu\text{m}$. When the thickness of the central mass is analysed at less than $50\mu\text{m}$, in this case with a $20\mu\text{m}$ thickness, the maximum stress obtained is 55MPa but a higher deflection of $2.8\mu\text{m}$ is obtained thereby increasing the non-linearity.

The side length of the central mass was varied from $(700-1400)\mu\text{m}$. It was found that with an increase in length not only the deflection decreases but also the maximum stress produced decreases. At $1400\mu\text{m}$ side length, the maximum stress produced was less than that of chosen $1200\mu\text{m}$ side length while the nonlinearity reduction was considerably less. When side length lesser than $1200\mu\text{m}$ was simulated, higher deflection was observed with slight increase in maximum stress generated. Hence $1200\mu\text{m}$ side length was found to be appropriate in terms of both better sensitivity and low non-linearity.

VII. CONCLUSION

This work analyses and evaluates a theoretical model of a square piezoresistive membrane with a centre mass and grooved structure. The proposed membrane was examined with respect to the standard membrane variants i.e. E and C type. The FEM analysis for the former was performed and the outcome of the simulations provided a fair balance between stress corresponding to the sensitivity and deflection of the membrane which corresponds to non-linearity. The central mass stiffens the membrane and the annular

grooved structure provides enhanced sensitivity for the membrane. The prospective membrane brought about an improved performance along the lines of sensitivity and linearization with respect to the compared membrane types.

AUTHOR DECLARATIONS SECTION

* **Ethics approval and consent to participate:** Not Applicable

* **Consent for publication:** Yes

* **Availability of data and materials:** Not Applicable

* **Competing interests:** Not Applicable

* **Funding:** Not Applicable

* **Authors' contributions:** All authors contributed to the study conception and design. Material preparation, simulation and analysis were performed by all the authors together. The first draft of the manuscript was written by Mr. Rohan Sahay and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

* **Acknowledgements:** Not Applicable

Compliance with Ethical Standards section

* **Disclosure potential conflicts of interest:** Not Applicable

* **Research involving Human Participants and/or Animals:** Not Applicable

* **Informed consent:** Not Applicable

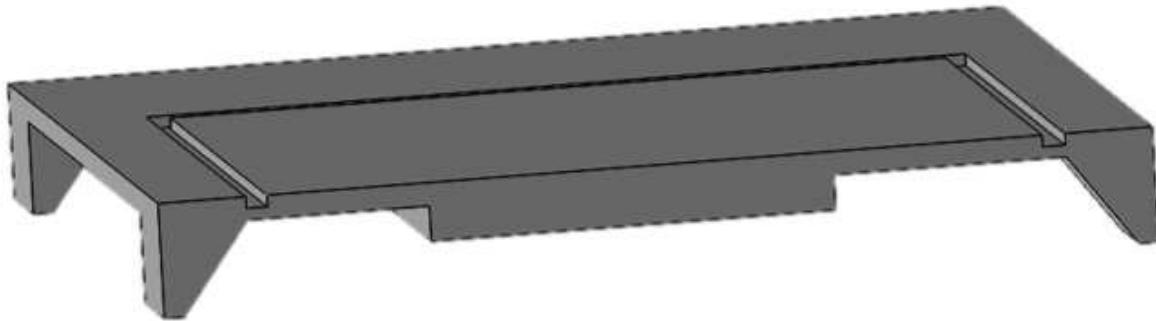
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Figures

(a)



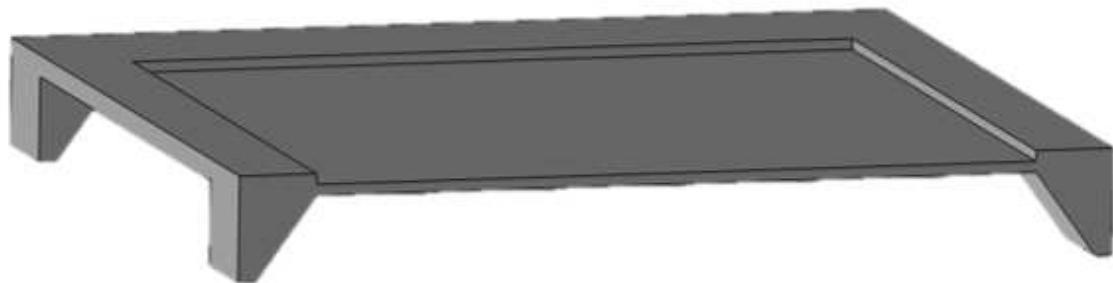
(b)



Figure 1

Structure of proposed membrane: (a) Front view (b) Rare view

(a)



(b)

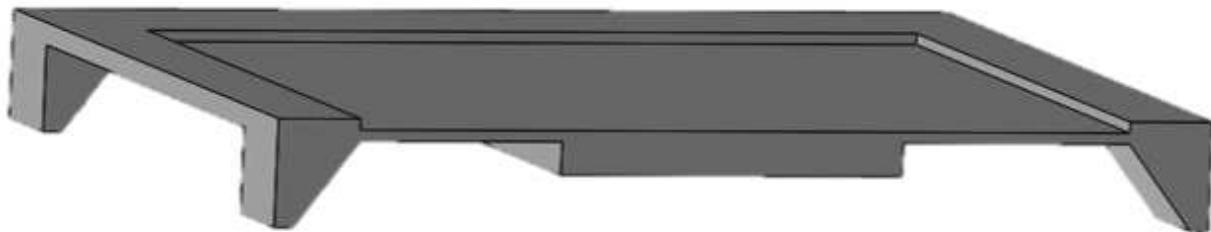
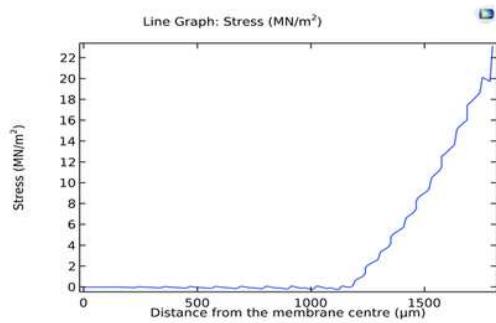


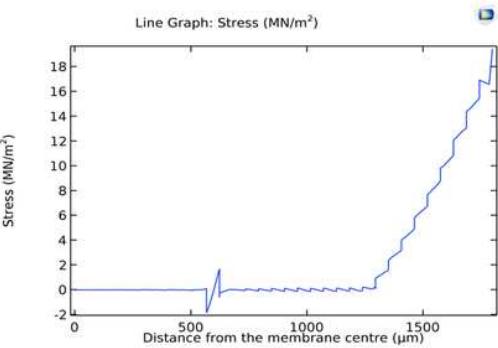
Figure 2

Conventional membranes: (a) C-type membrane (b) E-type membrane

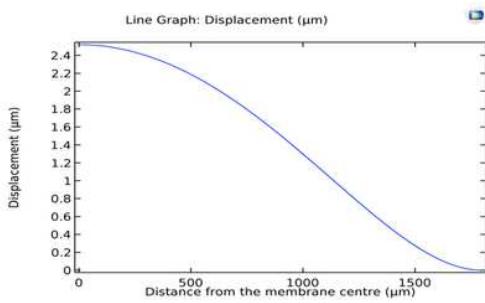
(a)



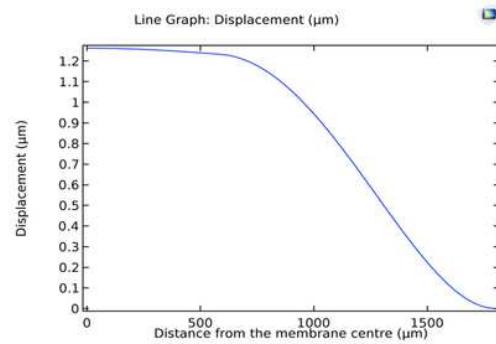
(c)



(b)



(d)

**Figure 3**

- (a) Stress for C-type membrane
- (b) Displacement for C-type membrane
- (c) Stress for E-type membrane
- (d) Displacement of E-type membrane

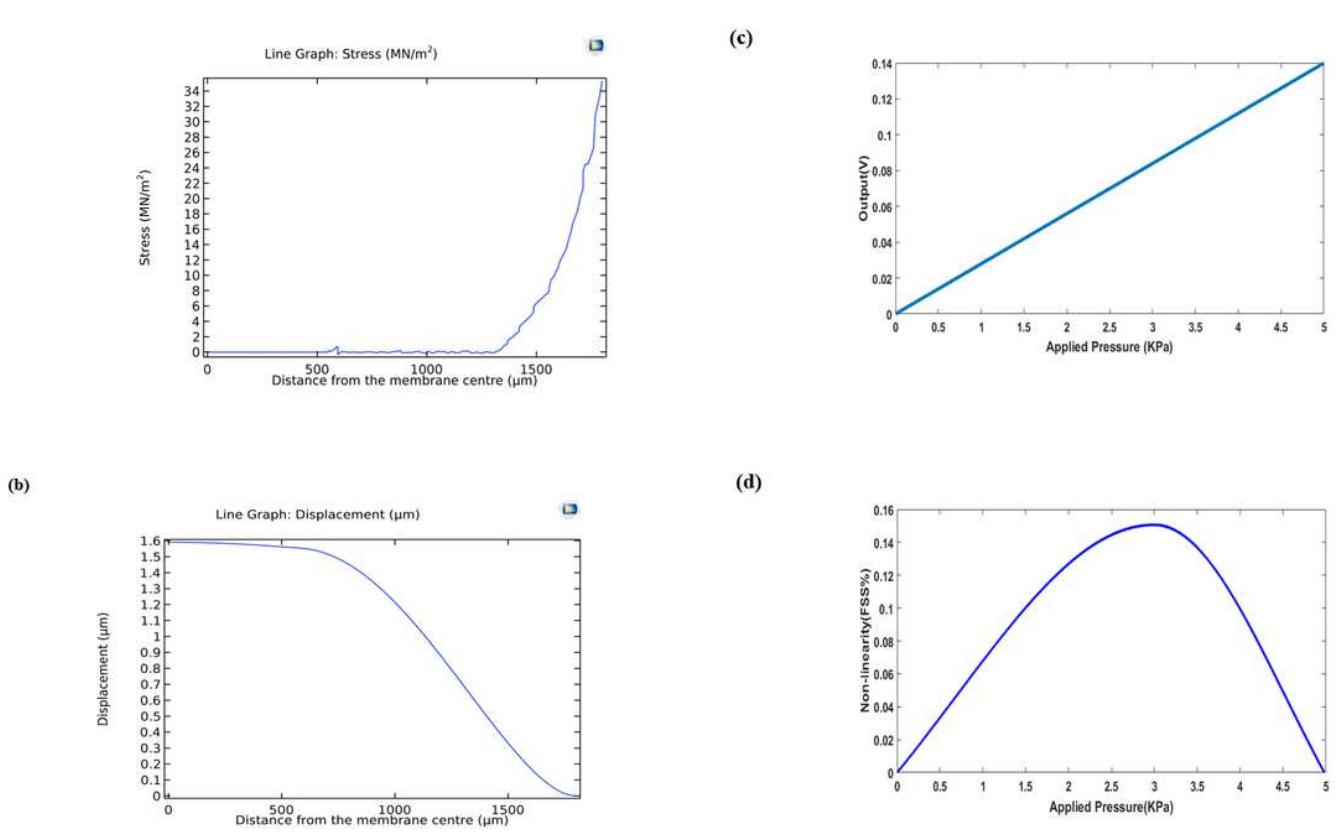


Figure 4

(a) Stress for proposed membrane (b) Displacement for proposed membrane (c) Output vs. applied pressure of proposed membrane (d) Non linearity vs. applied pressure for proposed membrane

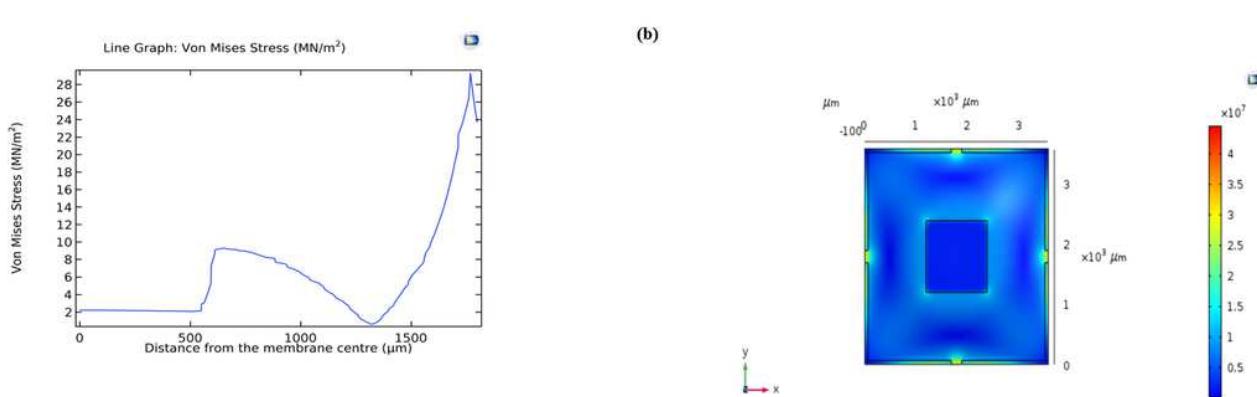
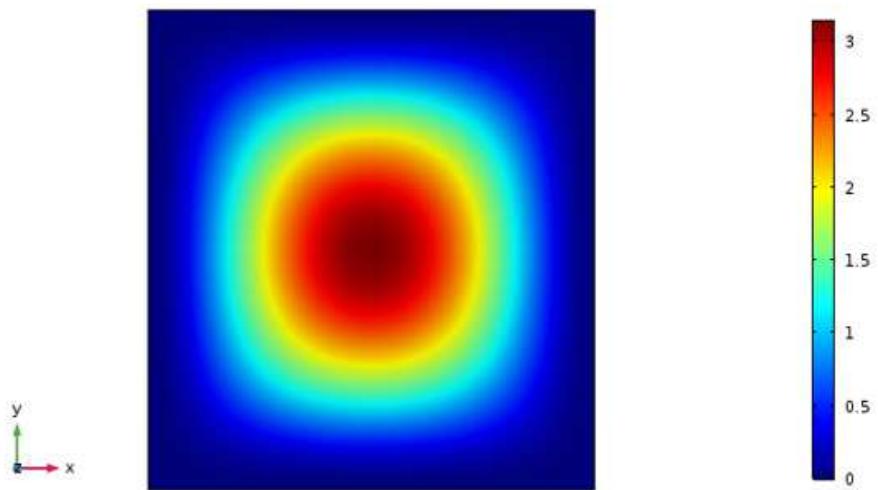


Figure 5

(a) Von-Misses stress (b) Surface Stress distribution for proposed membrane

(a)



(b)

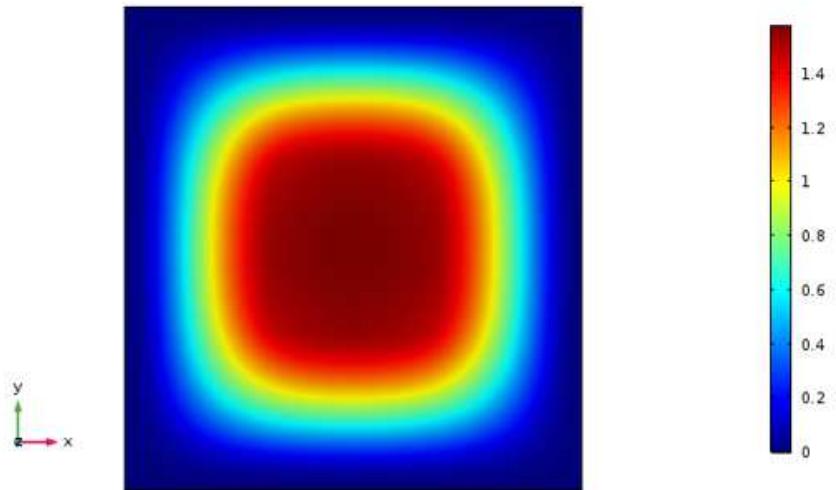


Figure 6

(a) Membrane deflection without central mass (C-type) (b) Membrane deflection with central mass (E-Type)